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QUANTIFYING THE MECHANICAL AND HYDROLOGIC EFFECTS OF RIPARIAN VEGETATION ON STREAMBANK STABILITY

ANDREW SIMON* AND ANDREW J. C. COLLISON
USDA-ARS National Sedimentation Laboratory, PO Box 1157, Oxford, MS 38655, USA

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ABSTRACT

Riparian vegetation strips are widely used by river managers to increase streambank stability, among other purposes. However, though the effects of vegetation on bank stability are widely discussed they are rarely quantified, and generally underemphasize the importance of hydrologic processes, some of which may be detrimental. This paper presents results from an experiment in which the hydrologic and mechanical effects of four riparian tree species and two erosion-control grasses were quantified in relation to bank stability. Geotechnical and pore-water pressure data from streambank plots under three riparian covers (mature trees, clump grasses and bare/cropped turf grass) were used to drive the ARS bank stability model, and the resulting factor of safety (F_s) was broken down into its constituent parts to assess the contribution (beneficial or detrimental) of individual hydrologic and mechanical effects (soil moisture modification, root reinforcement and surcharge). Tree roots were found to increase soil strength by 2–8 kPa depending on species, while grass roots contributed 6–18 kPa. Slope stability analysis based on data collected during bank failures in spring 2000 (following a very dry antecedent period) shows that the mechanical effects of the tree cover increased F_s by 32 per cent, while the hydrologic effects increased F_s by 71 per cent. For grasses the figures were 70 per cent for mechanical effects and a *reduction* of F_s by 10 per cent for the hydrologic effects. However, analysis based on bank failures in spring 2001 (following a wetter than average antecedent period) showed the mechanical effects of the tree cover to increase F_s by 46 per cent, while hydrologic effects added 29 per cent. For grasses the figures were 49 per cent and −15 per cent respectively. During several periods in spring 2001 the hydrologic effects of the tree cover *reduced* bank stability, though this was always offset by the stabilizing mechanical effects. The results demonstrate the importance of hydrologic processes in controlling streambank stability, and highlight the need to select riparian vegetation based on hydrologic as well as mechanical and ecological criteria. Published in 2002 by John Wiley & Sons, Ltd.

KEY WORDS: bank stability; riparian vegetation; matric suction; root reinforcement; transpiration

INTRODUCTION

Streambank retreat occurs by a combination of hydraulic-induced bank-toe erosion and bank mass failure. In addition to its effects in modifying hydraulic scour, and its undoubted benefits in terms of environmental quality, vegetation is widely believed to increase the stability of streambanks (Thorne, 1990; Simon and Darby, 1999). Stabilizing effects include reinforcement of the soil by the root system and the reduction of soil moisture content because of canopy interception and evapotranspiration. However, studies of vegetation's impact on the stability of hillslopes have highlighted the potential for some destabilizing effects (Greenway, 1987; Collison and Anderson, 1996). These include higher near-surface moisture contents during and after rainfall events due to increased infiltration capacity, and surcharge due to the weight of trees. Though many authors have evaluated the mechanical benefits of riparian vegetation (Abernethy and Rutherford, 2001), few have quantified the hydrologic effects, or considered the balance between potential stabilizing and destabilizing effects under different scenarios. This paper reports a field monitoring and computer-modelling investigation that has been carried out in northern Mississippi to quantify the separate and combined hydrologic and mechanical effects of three different vegetation covers on streambank stability.

* Correspondence to: A. Simon, USDA-ARS National Sedimentation Laboratory, PO Box 1157, Oxford, MS 38655, USA.
E-mail: asimon@ars.usda.gov

Streambank stability

Streambank collapse occurs when the driving forces (stress) exceed the resisting forces (strength). The shear strength of saturated soil can be described by the Mohr–Coulomb criterion:

$$\tau_f = c' + (\sigma - \mu_w)\tan\phi' \tag{1}$$

where τ_f = shear stress at failure (kPa); c' = effective cohesion (kPa); σ = normal stress (kPa); μ_w = pore-water pressure (kPa); and ϕ' = effective angle of internal friction (degrees).

In incised stream channels and in arid or semi-arid regions, much of the bank may be above the water table and will usually experience unsaturated conditions. Matric suction (negative pore-water pressure) above the water table has the effect of increasing the apparent cohesion of a soil. Fredlund *et al.* (1978) defined a functional relationship describing increasing soil strength with increasing matric suction. The rate of increase is defined by the parameter ϕ^b, which is generally between 10° and 20°, with a maximum value of ϕ' under saturated conditions (Fredlund and Rahardjo, 1993). Apparent cohesion incorporates both electrochemical bonding within the soil matrix and cohesion due to surface tension on the air–water interface of the unsaturated soil:

$$c_a = c' + (\mu_a - \mu_w)\tan\phi^b = c' + \psi\tan\phi^b \tag{2}$$

where c_a = apparent cohesion (kPa); μ_a = pore-air pressure (kPa); and ψ = matric suction (kPa).

The term ϕ^b varies for all soils, and for a given soil with moisture content (Fredlund and Rahardjo, 1993; Simon *et al.*, 1999, 2000). Data on ϕ^b are particularly lacking for alluvial materials. However, once this parameter is known (or assumed) both apparent cohesion (c_a) and effective cohesion (c') can be calculated by measuring matric suction with tensiometers or other devices and by using Equation 2.

Driving forces for streambank instability are controlled by bank height and slope, the unit weight of the soil and the mass of water within it, and the surcharge imposed by any objects on the bank top, bank surface, or within the bank mass such as trees. The ratio of resisting to driving forces is commonly expressed as the factor of safety (F_s), where values greater than one indicate stability and those less than one, instability. Streambank failure can occur by several mechanisms, including cantilever failures of undercut banks, toppling of vertically arranged slabs, rotational slumping, and wedge failures (Thorne *et al.*, 1981). The type of failure reflects the degree of undercutting (if any) by fluvial scour or other mechanisms, and the nature of the bank materials.

Effects of vegetation on bank stability

The impact of vegetation can be divided into mechanical and hydrologic effects, with further subdivision into stabilizing and destabilizing effects. Potentially beneficial effects of riparian vegetation on aquatic and riparian habitat are acknowledged but are beyond the scope of this investigation.

Mechanical effects. Soil is generally strong in compression, but weak in tension. The fibrous roots of trees and herbaceous species are strong in tension but weak in compression. Root-permeated soil, therefore, makes up a composite material that has enhanced strength (Thorne, 1990). Numerous authors have quantified this enhancement using a mixture of field and laboratory experiments. Endo and Tsuruta (1969) used *in situ* shear boxes to measure the strength difference between soil with and without roots. Gray and Leiser (1982) and Wu (1984) used laboratory-grown plants and quantified root strength in large shear boxes. Wu *et al.* (1979) developed a widely used equation that estimates the increase in soil strength (c_r) as a function of root tensile strength, areal density and root distortion during shear:

$$c_r = T_r(A_r/A)(\cos\theta\tan\phi + \sin\theta) \tag{3}$$

where c_r = cohesion due to roots (kPa); T_r = tensile strength of roots (kPa); A_r/A = area of shear surface occupied by roots, per unit area (root-area ratio); θ = shear distortion from vertical (degrees); and ϕ = friction angle of soil (degrees).

Root tensile strength can be measured in the laboratory or field and is highly variable, with typical values in the thousands to millions of pascals (see Gray (1978) for a comprehensive review of published data). Most authors note a non-linear inverse relationship between root diameter and strength, with smaller roots contributing more strength per unit root area. This has led several authors to suggest that the optimum species for slope stabilization are grasses and shrubs, which combine large numbers of small, strong roots with little surcharge. Clump grasses such as vetiver (*Vetiver zizinades*), Alamo switch grass (*Panicum virgatum 'Alamo'*) and eastern gamma grass (*Tripsacum dactyloides*), which have proved successful in reducing surface erosion (Dabney *et al*., 1997), have been advocated as potential bank-stabilizing species, in addition to woody riparian covers.

Although many authors have measured root tensile strength for a variety of upland woody and herbaceous species, little work has been done on riparian species and still less has been carried out on the root architecture of riparian vegetation. Abernethy and Rutherford's (2001) study in Australia stands out as an exception. Available data indicate that most roots are found within the upper 50–100 cm of the soil profile (Jackson *et al*., 1996; Sun *et al*., 1997; Tufekcioglu *et al*., 1999). More data are needed, however, to quantify the root area ratio (A_r/A) and shear zone root distortion terms.

In addition to stabilizing effects due to root reinforcement, vegetation can affect streambanks by increasing surcharge. Surcharge has both a beneficial and a detrimental effect; it increases the mass acting on a potential failure surface and increases normal stress and, therefore, shear strength due to friction. Whether the net effect is stabilizing or destabilizing depends on the slope of the shear surface and the effective friction angle (ϕ') of the soil, but in most cases it will be destabilizing due to the steep shear-surface slopes of streambank failures. Additional vegetative mechanical effects (both stabilizing and destabilizing) such as buttressing, anchoring and arching (Gray and Leiser, 1982; Coppin and Richards, 1990) are of limited significance in many fluvial environments and are, therefore, not considered here although they may be important in other environments.

Hydrologic effects. Vegetation increases bank stability by intercepting rainfall that would otherwise have infiltrated into the bank, and by extracting soil moisture for transpiration. Both processes enhance shear strength by reducing positive pore-water pressure and encouraging the development of matric suction. However, the hydrologic effects of riparian vegetation are even less well quantified than the mechanical effects. Although data are available on canopy-interception rates for many riparian tree species, there is little useful data on the degree to which vegetation dries out the material constituting streambanks. Canopy interception for deciduous tree species is typically in the range of 10–20 per cent (Coppin and Richards, 1990) but these figures represent annual averages for continuous closed canopies. A point that tends to be overlooked when discussing vegetation effects on bank stability is that most bank failures occur during the winter or early spring, when deciduous vegetation is dormant and canopies have been shed. In addition, the high rainfall events likely to be associated with bank failures tend to have the lowest canopy interception rates, since canopy interception is inversely proportional to rainfall intensity and duration (Dingman, 1994). Likewise, transpiration does not generally have much impact on soil moisture until mid-spring.

Although beyond the scope of this paper, it is useful to consider the hydrologic effects of riparian strips of varying width. Specific and net hydrologic effects (interception and transpiration) of wide strips of riparian vegetation may vary considerably from the narrow strips that are commonly found along incised streams. For example, this may be particularly important in reducing the delivery of laterally moving water across the floodplain/terrace towards the streambanks.

In contrast, vegetation has several effects that are detrimental to streambank stability. Canopy interception and stemflow tends to concentrate rainfall locally around the stem of plants, creating higher local pore-water pressures (Durocher, 1990), while root development and associated biological activity creates macropores that increase infiltration capacity and concentrate flow deeper into the bank. These effects are most pronounced during and immediately after large rainfall events of the type that are often associated with bank failure. Collison and Anderson (1996) used combined hydrology–stability modelling to simulate increased infiltration and preferential flow on vegetated slopes, and demonstrated that the beneficial mechanical effects of vegetation can be outweighed by detrimental hydrologic effects, leading to lower factor of safety values during intense rainstorms in some cases.

The hydrologic behaviour of streambanks is particularly important in incised and arid or semi-arid channels since these banks are normally unsaturated and are, therefore, sensitive to increases in moisture content.

Decreases in shear strength due to a loss of matric suction are a leading cause of bank failures in incised channels (Simon *et al.*, 1999, 2000). For non-incised channels in humid regions, however, streambanks may be expected to reach saturation during typical winter conditions, yet remain stable because they are not particularly high. Any detrimental hydrologic effects are likely to be much less significant, because common hydrologic conditions already represent a 'worst case'.

There is a general consensus in the literature that the main effects of vegetation on bank stability are mechanical rather than hydrological. To quote Coppin and Richards (1990, p. 65): 'Although the ability of trees to reduce soil moisture is recognized qualitatively, it has yet to be quantified. The magnitude of their influence on soil strength, however, is likely to be less than that of soil reinforcement by roots, especially at periods critical for slope stability.' To evaluate this common assumption, and assess the effectiveness of vegetation covers as stability enhancements, it is necessary to quantify all of those effects.

METHODOLOGY

Data were collected on the hydrologic and mechanical properties of three vegetation test plots on an unstable incised streambank in northern Mississippi. The data collected include intrinsic soil-mechanical properties (cohesion, friction angle, unsaturated strength parameter ϕ^b and unit weight) matric suction and pore-water pressure under three vegetation treatments, and root tensile strength and distribution for a range of species. The three vegetation treatments were control (short cropped turf/bare), eastern gamma grass (a tall clump grass), and a mature riparian tree stand (a mixture of sycamore (*Platanus occidentalis*), river birch (*Betula nigra*) and sweetgum (*Liquidambar styroflora*)). The data were used to parameterize a model of streambank stability that incorporates positive and negative pore-water pressures. Additional root data were collected on black willow (*Salix nigra*) and Alamo switch grass (*Panicum virgatum* 'Alamo'). Black willow is widely used in channel stabilization projects, and switch grass is used in erosion control locally.

Field data collection

Research was carried out at the Goodwin Creek Experimental Watershed in the Loess Hills region of northern Mississippi, with grass-root strength data collected at the nearby Nelson Farm site. Mean annual rainfall at the site is 1314 mm and climate is warm and humid. Channel straightening on the Tallahatchie River and its tributaries beginning around the start of the 20th century led to upstream channel degradation and associated bank widening. The study reach has been intensively monitored since 1997. The channel in the study reach has incised approximately 3 m historically, to a current depth of about 5 m. For at least the last four years the channel has been relatively stable in terms of depth, with slight aggradation accompanying lateral migration by mass failures on the outside of meander bends. Dendrochronology and a geomorphic evaluation on the opposing point bar indicates that lateral migration has been occurring for at least 30 years at an average rate of about 0·5 m a^{-1} (Simon and Darby, 1997). The bank cross section is steep, generally between 70 and 90°.

An Iowa borehole shear test (BST) device was used to measure the *in situ* shear strength of bank layers at different depths in a series of boreholes augered into the streambank. The BST enables direct measurements of apparent cohesion and friction angle to be made at ambient pore-water pressures (Luttenegger and Hallberg, 1981). A series of repeated tests were made in a small area, and matric suction was measured in an undisturbed core removed from the point where the BST was operated. In this way it was possible to calculate the unsaturated strength parameter ϕ^b to obtain the relationship between matric suction and effective cohesion using Equation 2. Core samples were also analysed for unit weight and particle size distribution.

To obtain data to parameterize the root-reinforcement equation, a series of trenches was dug alongside four common riparian tree species and two grass species outside the monitored plots: sycamore, black willow, sweetgum and river birch, and eastern gamma grass and switch grass. Roots were exposed and tested for tensile strength using a technique developed by Abernethy and Rutherford (2001). The diameters of individual roots were measured using calipers, and the roots were then attached to a load cell using a cable grip or clamp. Stress was applied through the load cell using a winch, and the load and displacement were recorded electronically. Stress was increased until the root failed, either by snapping or by pulling out. Peak stress at failure and root diameter was then recorded. To obtain data on root architecture and distribution, additional trenches were excavated, and the root diameter, orientation and distribution measured. All trees were cored and their age calculated using dendrochronology.

Surcharge due to the mature riparian trees was calculated by multiplying the mass of trees by the stocking density (number of trees per unit area). Tree volume was estimated using De Vries (1974) method:

$$V = L\frac{\pi(\mathrm{d1}^2 + \mathrm{d2}^2)}{8} \tag{4}$$

where V = volume of wood (m^3), $d1$ = diameter of trunk at base (m), $d2$ = diameter of trunk at top (m), and L = length of trunk (m). Volume was converted to mass using an average density of 0·96 g cm^{-3} measured for live sycamore, sweetgum and river birch trees in northern Mississippi (Shields *et al.*, 2001).

Bank hydrology was monitored using tensiometers which recorded pore-water pressure (positive and negative) every ten minutes. At each of the three vegetation treatment plots, a nest of five tensiometers was installed, at depths of 30, 100, 200, 270 and 433 cm (corresponding to different sedimentary layers within the bank profile). Streamflow level was also recorded every ten minutes using two submerged pressure transducers mounted in the channel. Open sky rainfall, stemflow and canopy throughfall under the riparian tree plot were recorded on tipping bucket rain gauges every ten minutes, with an additional array of 12 manual rain gauges (ten in the woody stand and two in the open) measuring rainfall and throughfall every day on which rain occurred.

Numerical modelling of bank stability

To assess vegetation effects on bank stability, hydrologic and mechanical data were used in a numerical model of bank stability. The ARS bank stability model is a further development of the wedge failure type developed by Simon and Curini (1998) and Simon *et al.* (1999, 2000), which in turn is a refinement of the models developed by Osman and Thorne (1988) and Simon *et al.* (1991). The model is a limit equilibrium analysis in which the Mohr–Coulomb failure criterion is used for the saturated portion of the wedge, and the Fredlund *et al.* (1978) criterion is used for the unsaturated portion. In addition to positive and negative pore-water pressure, the model incorporates layered soils, changes in soil unit weight based on moisture content, and external confining pressure from streamflow. The model divides the bank profile into up to five user-definable layers with unique geotechnical properties.

The factor of safety (F_s) is given by (Simon *et al.*, 1999, 2000):

$$Fs = \frac{\sum c_i' L_i + [S_i \tan{\phi_i}^b] + [W_i \cos\beta - U_i + P_i \cos(\alpha - \beta)]\tan\phi_i'}{\sum W_i \sin\beta - P_i \sin[\alpha - \beta]} \tag{5}$$

where c_i' = effective cohesion of ith layer (kPa); L_i = length of the failure plane incorporated within the ith layer (m); S = force produced by matric suction on the unsaturated part of the failure surface (k Nm^{-1}); W = weight of the ith layer (kN); U = the hydrostatic-uplift force on the saturated portion of the failure surface (kN m^{-1}); P = the hydrostatic-confining force due to external water level (kN m^{-1}); α = failure-plane angle (degrees from horizontal); and β = bank angle (degrees from horizontal).

The validity of using a wedge failure model to assess bank stability is open to debate, since banks collapse by a variety of failure mechanisms (see discussion above), and cohesive banks may be represented by rotational failure models. However, the field evidence from Goodwin Creek and other sites with largely frictional bank material suggests that the wedge model is appropriate.

When driven with temporally and spatially distributed pore-water pressure data from the tensiometer nests, the output is a time series of F_s. In this study the model was parameterized with data from each of the three vegetation plots. Identical bank profiles and intrinsic soil-strength properties (c', ϕ', ϕ^b) were used for all three plot simulations (Figure 1), while measured pore-water pressures, soil weight due to moisture content and increased cohesion due to roots (c_r) were applied uniquely to each plot. For the mixed tree plot averaged values

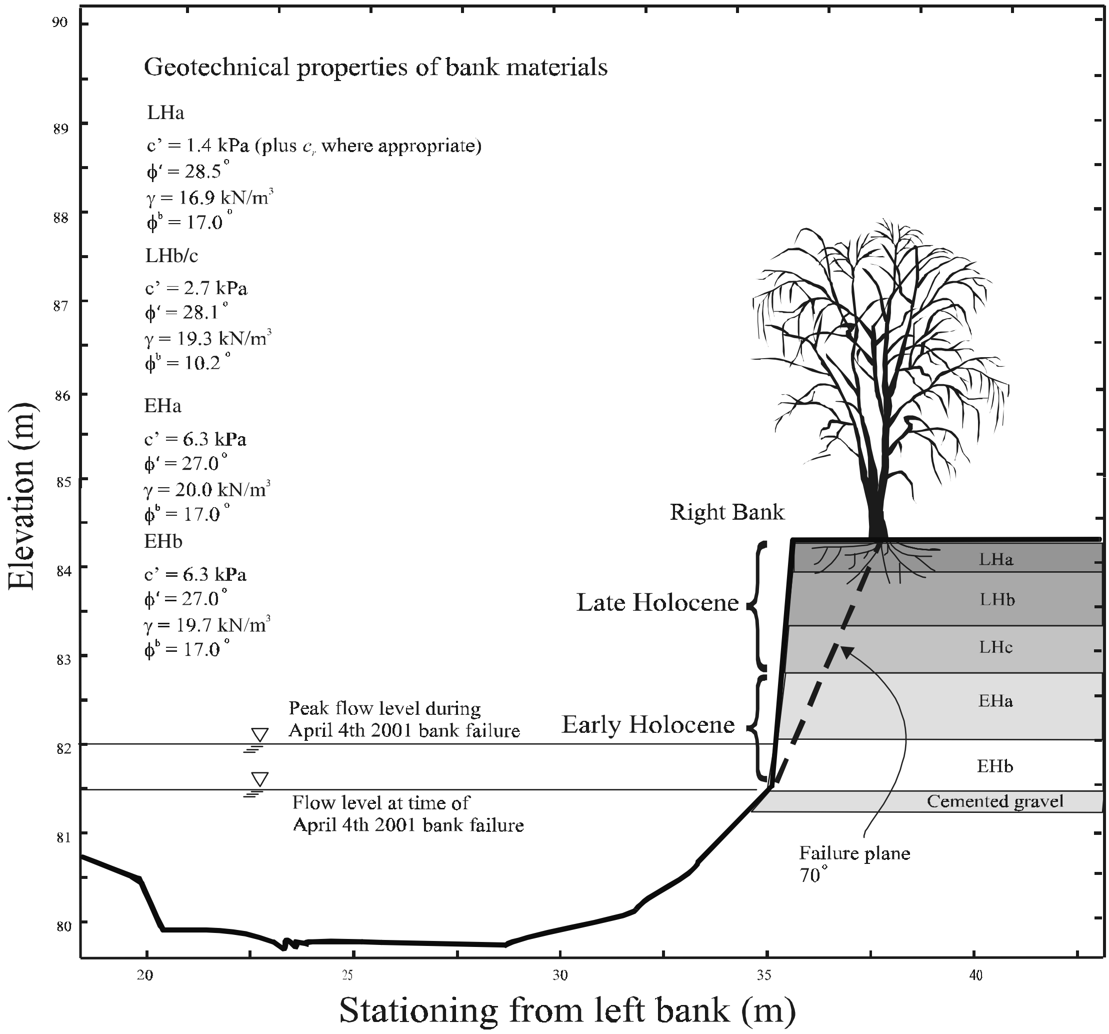

Figure 1. Streambank profile and geotechnical parameters of the test plots, Goodwin Creek, Miss., USA

of c_r and root depth distribution were used to reflect the three species. Surcharge due to the riparian tree cover was incorporated by increasing the unit weight of the upper 50 cm soil layer by an amount corresponding to the average load from the trees, divided by the root plate area. In addition to the combined-effect simulations, model runs were carried out isolating the individual effects of root reinforcement, pore-water pressure and surcharge to enable quantification of these components. Additional simulations were performed using the mechanical effects of two alternative covers: black willow and Alamo switch grass. Since independent pore-water pressure data were not available for these treatments we assumed that pore-water pressure under black willow was identical to that recorded under the riparian tree cover, and that switch grass could be represented by data from the gamma grass cover.

RESULTS

Intrinsic bank properties

Bank stratigraphy can be divided into two main Holocene units approximately 1·5 and 2 m thick, respectively, overlying a layer of slightly cemented sand and gravel (Figure 1, Table I). The late Holocene (upper)

Table I. Soil properties used in bank stability model

	Late Holocene (a)	Late Holocene (b)	Late Holocene (c)	Early Holocene (a)	Early Holocene (b)
Thickness (m)	0·5	0·6	0·6	0·7	1·3
Cohesion (kPa)	1·4	2·7	2·7	6·3	6·3
Friction angle (degree)	28·5	28·1	28·1	27·0	27·0
Unit weight (kN m^{-3})	16·9	19·3	19·3	20·0	19·7
ϕ^b	17·0	10·2	10·2	17·0	17·0

Increases in cohesion due to roots are added to Lower Holocene (a) scaled to allow for thickness. Lower Holocene (b/c) is divided to allow for different pore-water pressures.

unit can be further subdivided into two layers with the upper 0·5 m representing loess-derived alluvium defined locally as the Post Settlement Alluvium (Grissinger *et al.*, 1982). Shear strength testing shows the late Holocene unit to be largely frictional with little or no cohesion (<3·0 kPa). Most of the apparent cohesion in this layer is due to matric suction. The early Holocene (lower) unit by comparison has considerable cohesion (6·3 kPa), and acts as a semi-permeable boundary below the upper layer, contributing to the development of higher moisture contents and pore-water pressures in the late Holocene unit after rainfall. Observed shear planes did not intersect the cemented sand and gravel layer at the base of the Holocene units and was, therefore, not considered in stability analyses. Geotechnical properties of the Holocene units are shown in Figure 1. (The units are subdivided to permit variations in pore-water pressure within the units to be incorporated in the modelling.)

Mechanical effects of vegetation

Fifty trees were sampled, divided approximately evenly between the four species (Table II). There is some variability in mean age, which makes caution necessary when interpreting the results. The black willow specimens were youngest (mean age of five years), compared with mean ages of seven years for river birch and sycamore and 10 years for sweetgum. The grasses were five years old. Root tensile strength varies widely, both within and between species, with two orders of magnitude variability (2–125 MPa). Black willow has the weakest roots of the woody species (median strength 12 MPa) while sycamore has the strongest (23 MPa). Gamma grass roots have a median strength of 28 MPa, compared with 19 MPa for switch grass.

Comparison of root tensile strength with diameter reveals a set of non-linear inverse relationships similar to those found by other investigators (Figure 2). Analysis of variance shows sycamore to be significantly stronger than all other species except river birch ($p < 0{\cdot}05$). Considering roots of the same size (2–3 mm diameter class) to eliminate the effects of diameter on tensile strength, sycamore roots are strongest (mean tensile strength of 45 MPa), followed by river birch and sweet gum (22 and 18 MPa respectively), gamma grass (17 MPa), black willow (13 MPa) and switch grass (8 MPa). This shows that the high median strength of gamma and switch grass roots is due to the preponderance of small, strong roots rather than inherently superior strength properties.

The majority of roots sampled were relatively small (Table II) with maximum diameters in the range of 9–16 mm for woody species, and 2·5–3·0 for grasses. The root distribution study showed a marked decline in root area with depth below 20 cm for all species except river birch, sycamore and switch grass (Figures 3–5). No roots were found below 90 cm for any species except switch grass, though it is recognized that our sampling method precludes the discovery of vertical roots directly beneath the tree trunk. A useful measure of root distribution is to calculate the depth above which 90 per cent of all roots are found. For the species investigated the values were as follows: eastern gamma grass 17 cm, black willow 32 cm, sweetgum 38 cm, river birch 56 cm, switch grass 67 cm and sycamore 74 cm. Root orientation was mostly horizontal to approximately 30° for all species except switch grass, which had a largely vertical orientation.

Root distribution reveals three broad groups (Figures 3–5): black willow and sweetgum, river birch and sycamore, and the grass species. Black willow and sweetgum have relatively few roots per unit area, distributed

Table II. Summary of root properties

	Sycamore		River birch		Sweetgum		Gamma grass		Black willow		Switch grass	
	Diam.*	Strength†	Diam.*	Strength†	Diam.*	Strength†	Diam.*	Strength†	Diam.*	Strength†	Diam.*	Strength†
Median	3·1	22·9	3·2	15·9	4·8	12·0	1·4	27·7	2·5	12·0	1·3	19
Minimum	0·7	1·6	1·1	2·1	1·1	1·9	0·5	4·1	0·9	1·2	0·1	1·9
Maximum	11·1	124·7	10·9	69·6	11·4	56·9	2·5	97·6	15·8	70·4	4·7	128
Number of roots	117	117	66	66	56	56	76	76	137	137	1241	72
Number of plants	11		10		13		5		16		5	
Mean age (years)	7		7		12		5		5		5	
R_{90}	74		56		38		17		32		67	
Mean Ar/A	$1·2 \times 10^{-4}$		$1·1 \times 10^{-4}$		$5·6 \times 10^{-5}$		$4·4 \times 10^{-5}$		$8·7 \times 10^{-5}$		$1·4 \times 10^{-4}$	
c_r	7		8		4		6		2		18	

* Root diameter (mm).
† Root tensile strength (MPa).
R_{90}, Depth above which 90 percent of roots are found (cm).
Ar/A, Area of roots per unit area, averaged over 1 m depth of soil.
c_r, Additional cohesion due to roots (kPa) averaged over 1 m depth of soil.

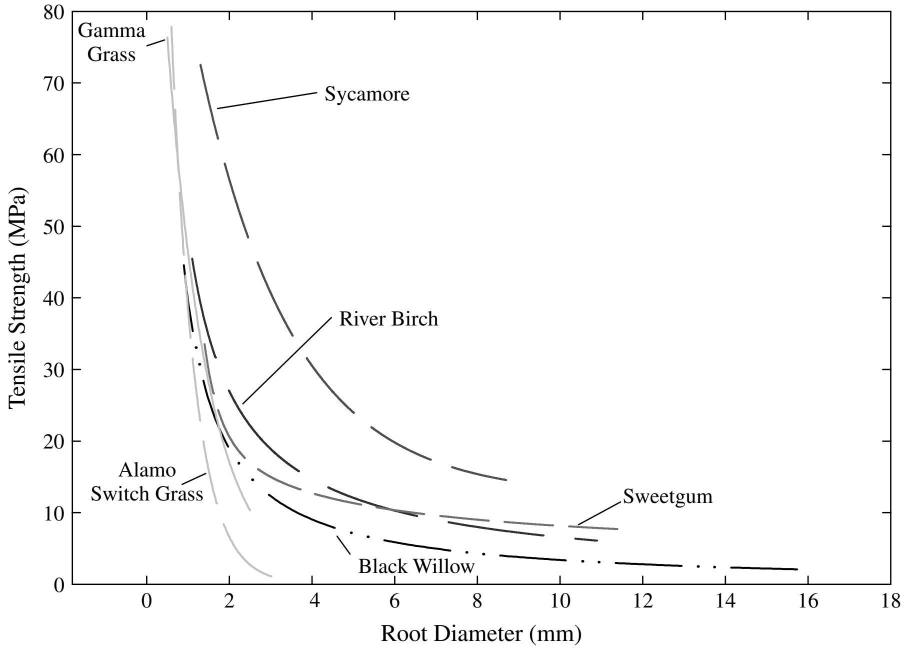

Figure 2. Relationship between root diameter and tensile strength for six vegetation species

mostly in the upper 20–30 cm, with most roots smaller than 2 mm in diameter. River birch and sycamore have roughly double the number of roots, a more even distribution that extends down to 80 cm, and roots mostly smaller than 1 mm. Both grass species have one to two orders of magnitude more roots per unit area than the woody species, a shallow concentration (20–30 cm depth) and are dominated by roots smaller than 1 mm in diameter. Of all the species switch grass has by far the greatest number of roots per unit area.

When root area ratio is considered, more differences emerge (Figure 4). Switch grass has the highest root area ratio ($1{\cdot}4 \times 10^{-4}$ averaged over the upper 1 m of soil), followed by river birch and sycamore ($1{\cdot}1 \times 10^{-4}$ and $1{\cdot}2 \times 10^{-4}$). For black willow, sweetgum and gamma grass the figures were, $8{\cdot}7 \times 10^{-5}$, $5{\cdot}6 \times 10^{-5}$ and $4{\cdot}4 \times 10^{-5}$ respectively. Black willow and sweetgum derive most of their root area ratio from a very small number of relatively large (>5 mm diameter) roots in the upper 20–30 cm. River birch and sycamore have more even distributions of area with depth, but again derive most of their root area from roots in the two largest size classes, despite a preponderance of smaller roots. Gamma grass has a similar root area ratio distribution to black willow and sweetgum, but derives most of the area from roots in the 1–2 mm diameter class. Switch grass has a much higher root area ratio than any other species, mostly due to roots in the 1–3 mm classes.

By combining the root architecture data with the root diameter–tensile strength relationships developed above, and analysing the data with the Wu *et al.* (1979) equation, it is possible to calculate the distribution of root reinforcement with depth for each species (Figure 5). River birch and sycamore have the strongest root-reinforcement effect of the woody species, with an average of 8 and 7 kPa cohesion due to roots respectively in the upper 1 m of soil, compared with 4 kPa for sweetgum, and 2 kPa for black willow. For eastern gamma grass the figure is 6 kPa, while switch grass has the greatest increase with 18 kPa. Breaking down the cohesion due to roots to assess the contribution made by roots of different sizes (Figure 5), it can be seen that most of the strength for woody species comes from larger (>5 mm diameter) roots. This finding goes against the widely held view that more reinforcement can be obtained from a large number of small roots with a greater tensile strength per unit area, rather than large, weaker roots. In general, root area is more important than root strength for woody species. Among the grasses this is also the case: switch grass has the greatest cohesion due to roots because of its extremely high root area, rather than having stronger roots.

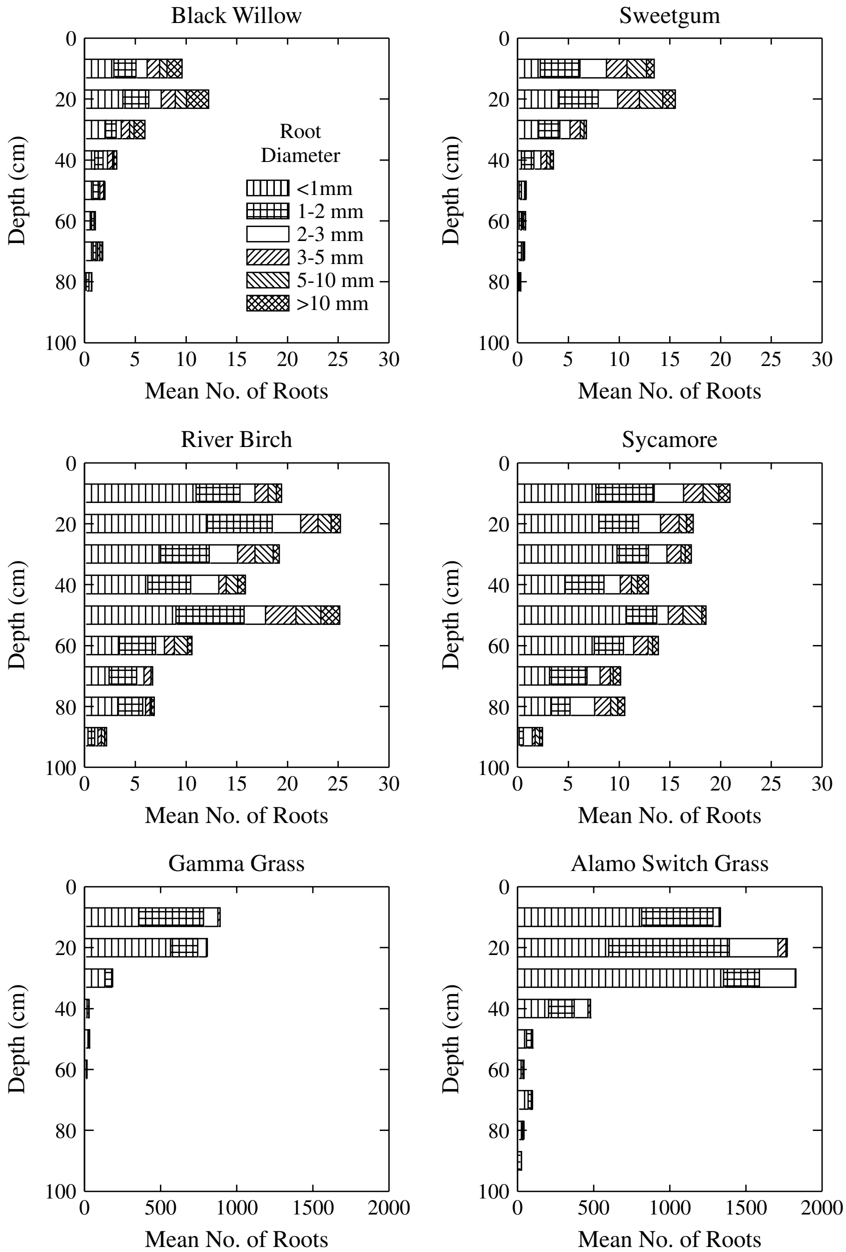

Figure 3. Distribution of root numbers with depth, subdivided by root diameter

For all species the reinforcement is concentrated mostly in the upper 50 cm of soil. The decline in strength with depth is most marked in the black willow and sweetgum trees, and gamma grass, where almost all roots lie in the upper 20–30 cm. The distribution of strength with depth is important, since field evidence suggests that where most of the reinforcement is concentrated in a shallow root mat (<20 cm) with a sharp boundary, bank failure can occur beneath the mat, reducing or possibly eliminating the contribution of the roots to overall bank strength.

Average diameter of the trees in the woody vegetation plot is 0·41 m at the trunk base and 0·2 m at the top, height is 18 m, and root plate radius (assumed to be half mean distance between trees) is 2·1 m ($n = 10$).

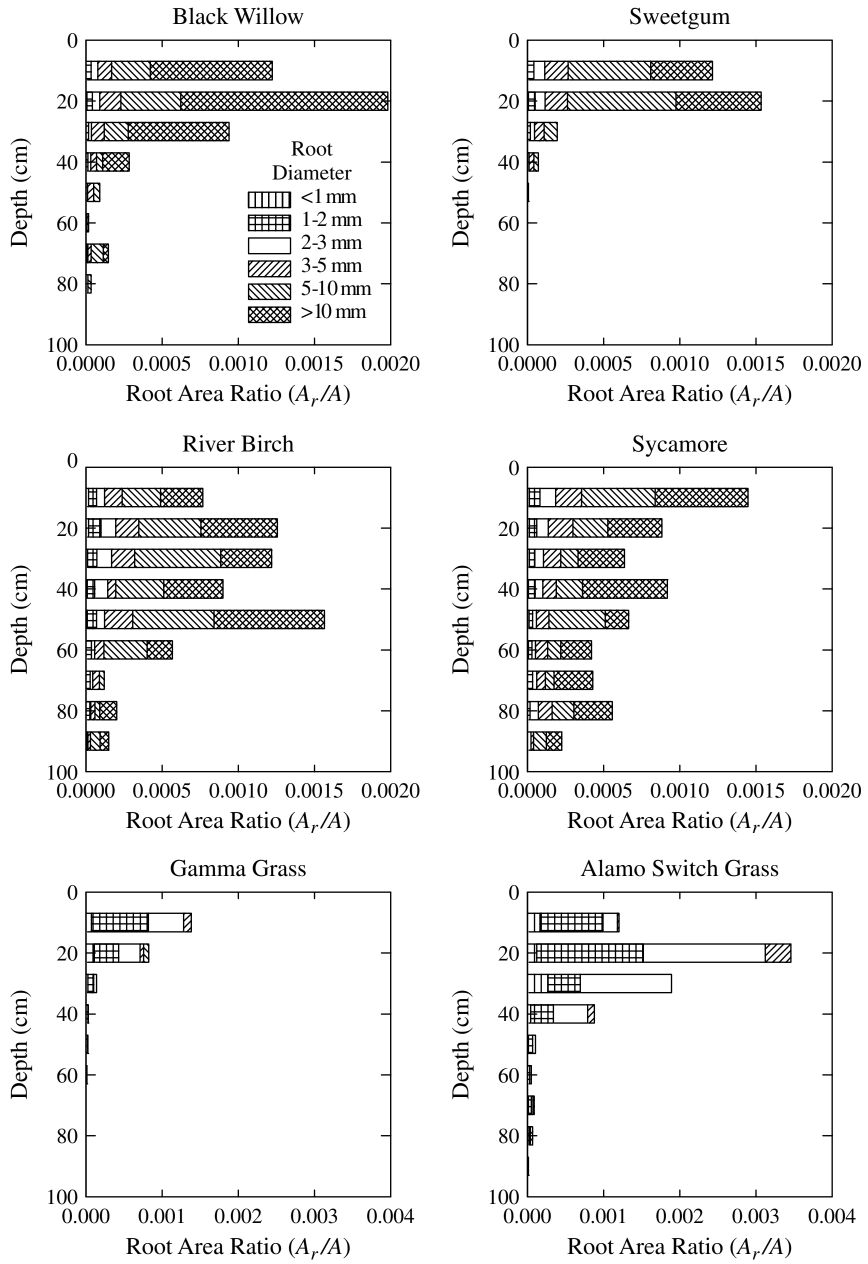

Figure 4. Distribution of root area ratio with depth, subdivided by root diameter

Using De Vries' equation (Equation 4) and tree density data from Shields *et al.* (2001) gives an average tree weight of approximately 1700 kg. Distributed over the root plate area and converted to force this gives a surcharge of 1·2 kPa. This is the equivalent of increasing the unit weight of the upper 50 cm of soil by 2·3 kN m^{-3} (12 per cent for a saturated soil).

Hydrologic effects of vegetation

Canopy interception under the mixed tree plot was negligible during the study period, accounting for 3 per cent of total rainfall. This figure is low compared to typical literature values for deciduous woodland, but is

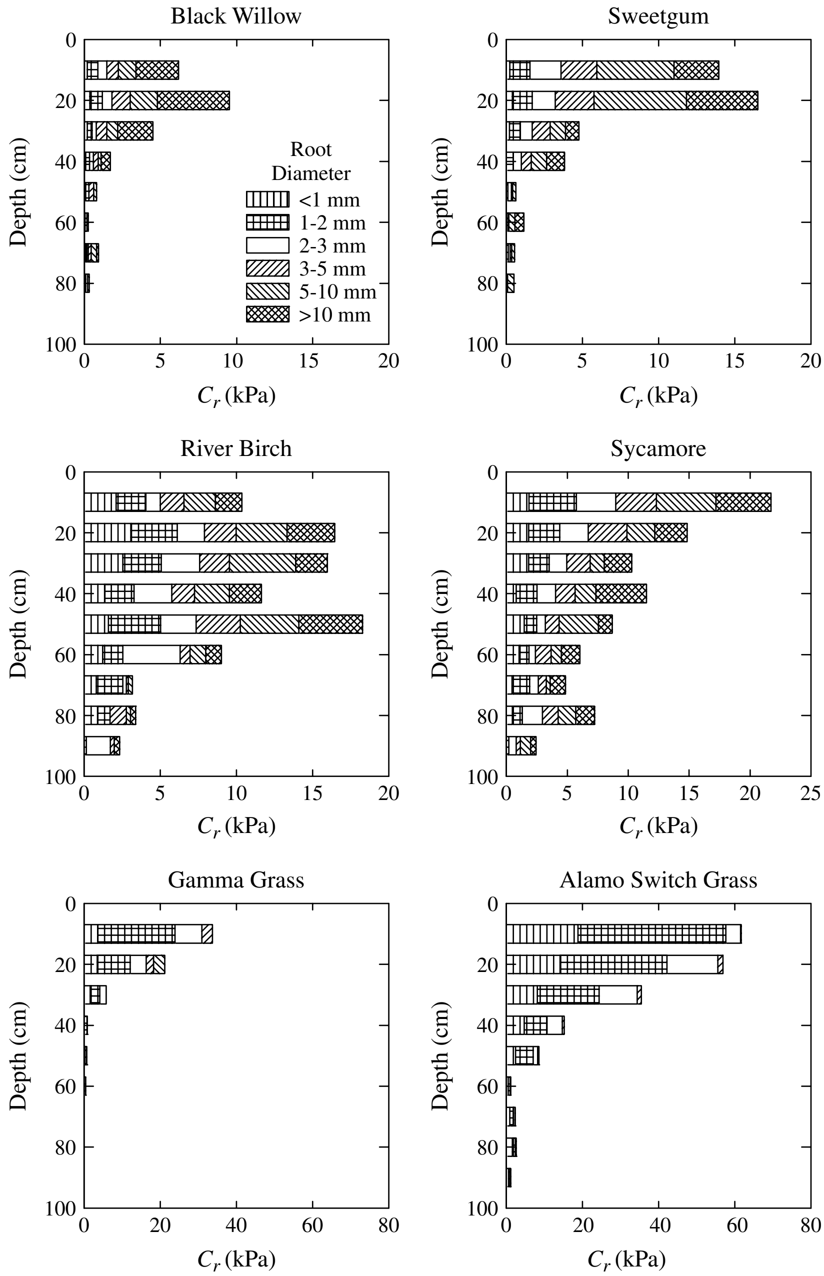

Figure 5. Distribution of cohesion due to roots with depth, subdivided by root diameter

largely explained by the narrowness of the riparian strip and the seasonality and intensity of rainfall in the area. The riparian strip is approximately 10 m wide, permitting some rainfall to blow in under the canopy. Approximately two-thirds of annual rain falls between October and April, when canopy cover is absent. In addition, summer rain mostly occurs in very high intensity events that greatly exceed the storage capacity of the canopy and pass through as throughfall. In some respects the canopy had adverse effects on bank stability; although stemflow was small in percentage terms when weighted for canopy area, it provided a concentrated source of water for infiltration around the tree trunk. Delivery of effective rainfall around the trunk was orders of magnitude higher than the average rainfall rate over the whole canopy area, with several events contributing more than 10 litres of stemflow.

Pore-water pressure monitoring reveals significant differences between the three vegetative covers (Figure 6). Note that due to an artificial irrigation experiment during July 2000, data for this period have been removed from the record. The tensiometers used to monitor pore-water pressure have an upper limit of 83 kPa, above which values appear to ‘flat line’. At 30 cm (Figure 6, top left) there is little difference between the plots during winter and spring, although the tree cover is slightly wetter (lower matric suction) than either clump grass or the control site from December 1999 until May 2000. During summer and autumn very high suctions are developed. A striking feature of all of the records is the difference between the tree plot and the other two plots prior to the onset of the winter, wet season. Matric suction under the tree plot is 40 to 60 kPa higher than under the other treatments. The tree cover experiences brief periods of ‘negative suction’ (positive pore-water pressure) after rainfall events in the spring, indicating increased infiltration capacity and the development of a perched water table in the root zone. The steep decline in suction under this cover indicates enhanced infiltration rates via macropores, probably along root pathways. This represents one of the potential detrimental effects of woody vegetation. After May, the tree site dries out faster than the other sites owing to greater rates of evapotranspiration, rising above the maximum measurable suction of 83 kPa by August.

Comparison of the tensiometer results from 100 cm reveals significant differences between all three covers. The control site and the grass plot broadly track each other, with the control consistently maintaining a suction around 10 to 20 kPa higher than the grass, indicating that stemflow may be concentrating water to depth in the grass plot (Figure 6, top right). This is even more pronounced in the tree plot, further pointing to the potential negative effects of rapid delivery of water along root- and faunal-induced macropores. Evidence for preferential macropore flow is not confined to the vegetation covers, however, with all three treatments showing response times to the 4 April event that exceed matric conductivities.

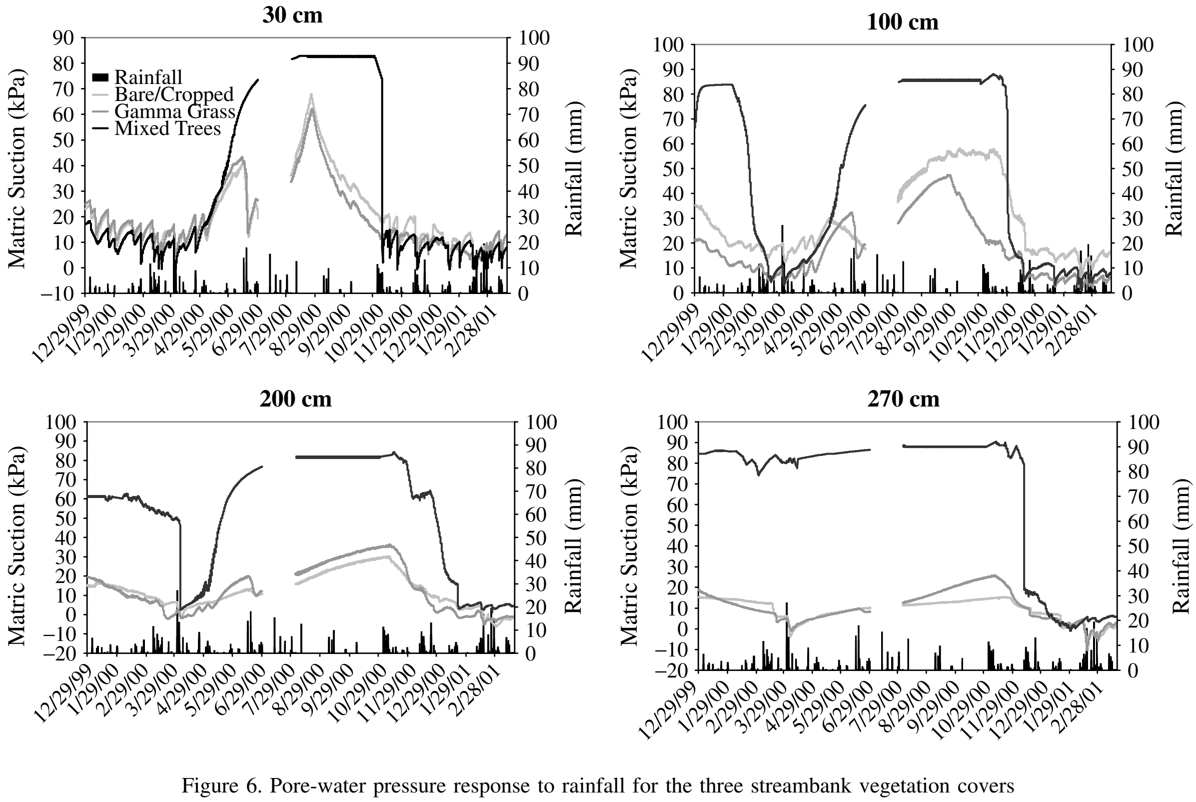

Figure 6. Pore-water pressure response to rainfall for the three streambank vegetation covers

In general, the deeper the tensiometer, the slower the response to the onset of rainfall under all treatments as rainwater infiltrates from the surface downward. The tree cover shows the maintenance of the previous summer's soil-moisture deficit through February 2000, at which point rapid wetting occurs at 100 cm. This wetting is associated with a series of relatively small rainfall events and the effect is translated to the deeper tensiometers with time as the 270 cm instrument begins to respond in early April (Figure 6, bottom right). The 270 cm tensiometer also demonstrates the threshold effects of wet winter conditions: throughout the 1999–2000 winter high tensions were maintained at this depth suggesting that all water was absorbed by dry soil higher in the profile, but in December 2000 a threshold was clearly crossed and rapid wetting occurred at this depth.

The tensiometer data suggest that there is relatively little hydrologic difference between clump grasses and a control (cropped grass/bare) cover, except during rainfall events when there is evidence for higher infiltration rates and preferential flow under the grass cover. The cropped grass/bare area of the control site was observed to recover from the winter faster than the clump grass, which has a longer dormant period. There is some evidence from the tensiometers to suggest that the control cover was transpiring earlier, and that the clump grasses did not start to transpire until May. This is supported by field observations of stem growth at around the same time.

Although the streambank under the tree cover maintained the greatest average values of matric suction, and, therefore, provided hydrologic benefits most of the time, rapid wetting at depth during spring 2001 led to brief periods when the tree plot was wetter than either the grass or bare plots, and thus caused a detrimental hydrologic effect.

Bank stability modeling

To incorporate the mechanical effects of the vegetation within the numerical scheme of the model and to maintain the depth-dependency of the reinforcement and surcharge data, additional layers were added to those shown in Figure 1. Table I provides a summary of the geotechnical data used in each layer. Figure 7 shows output from the bank stability model for the period September 1999 to March 2001, showing estimated F_s for the three vegetation plots. Values below 1 indicate predicted mass failure. Two periods of observed mass failure are indicated, in April 2000 (bare site only) and February 2001 (bare and grass sites). The model successfully captured these failures, with F_s less than 1 for the plots at the time of failure, but at no other

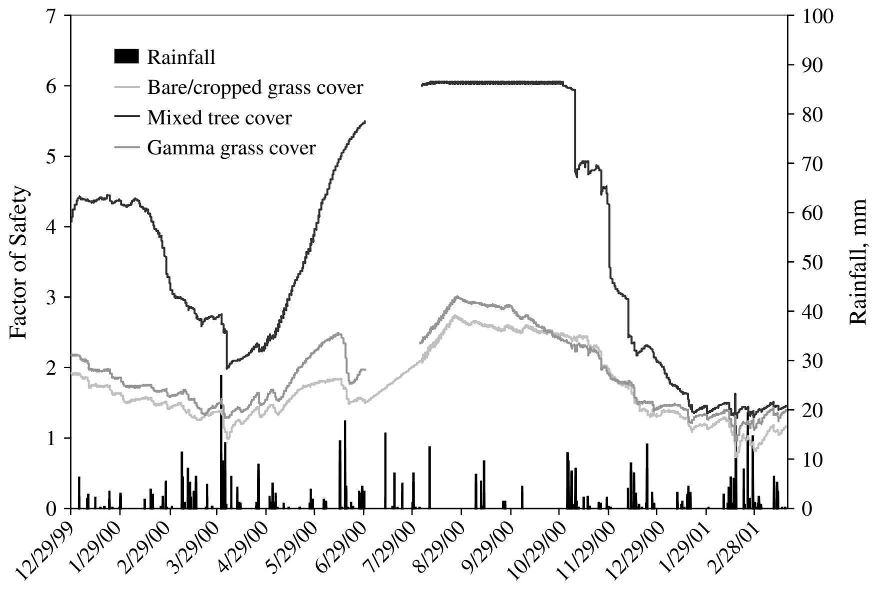

Figure 7. Factor of safety versus time for the three streambank vegetation covers

time. The figure clearly shows the increased stability due to the tree cover at the start of winter 2000, with the previous summer and autumn's soil moisture deficit maintaining high matric suction and stability. During the same period grass had approximately the same pore-water pressure distribution as the bare site, and the increase in F_s was due to root reinforcement. Rainfall preceding the April 2000 bank failure markedly reduced the F_s of the tree-covered bank, but at the point of failure it still had a F_s value of 1·99, compared to 1·22 for the grass site and 0·98 for the bare site. As late spring began, F_s under all three covers rose in response to higher matric suctions, with the greatest recovery occurring under the tree cover as transpiration picked up. A very large soil moisture deficit was built up under the tree cover, which provided protection through to January 2001. During the wetter than average winter of 2000/01 we saw a greater decline in F_s under all three covers, culminating in a second set of failures that occurred during February–March 2001.

Evaluating components of bank stability due to vegetation

The periods of observed bank failure provide us with an opportunity to break down the contributions of vegetation to bank stability, by using the model to assess each attribute (root reinforcement, surcharge and modified pore-water pressure) separately and in combination. The April 2000 period was initially taken and separate simulations were performed adding in each component one at a time to identify the addition or subtraction from net F_s (Figure 8, Table III). The figure shows F_s for the bare soil as the basic condition, with stabilizing effects on top and destabilizing effects shown below. Bare ground F_s during this period was 0·98, reflecting the bank failure of 4 April. F_s on the gamma grass plot was increased by 35 per cent by adding in root reinforcement effects, but reduced by 10 per cent due to the detrimental effects of wetter soil conditions, to give a net increase of 25 per cent. For the mixed tree cover root reinforcement increased F_s by 39 per cent. Strikingly, the hydrologic effects were more beneficial than the mechanical effects, increasing F_s by 71 per cent. Surcharge reduced F_s by 7 per cent, leaving a net F_s of 1·99 (103 per cent increase).

In order to evaluate the effectiveness of individual species for bank stabilization, data from the root studies were applied in the stability model. Since there is only a single hydrologic plot for riparian trees, this was taken as the condition for all four tree species. An average value of surcharge was applied to all trees except black willow, for which a value of half the average was used to reflect the smaller specimens found. For switch grass, hydrologic data from the gamma grass plot were used. While the substitution of hydrologic

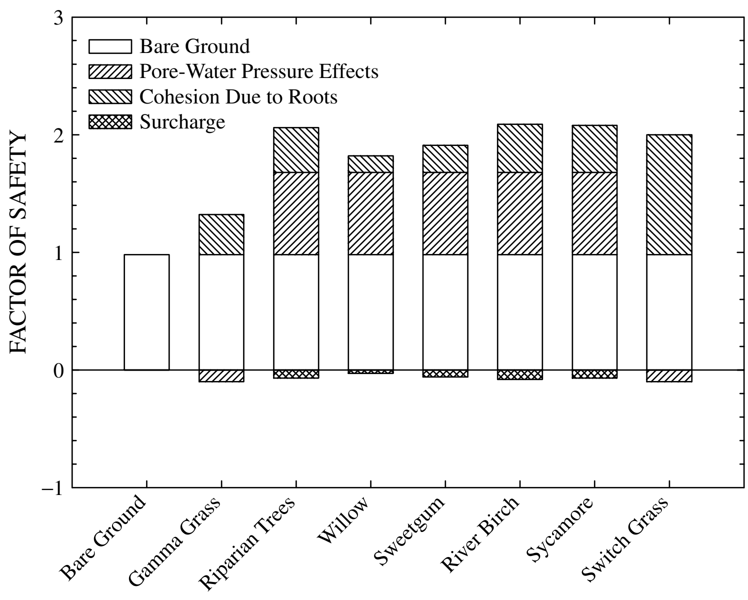

Figure 8. Minimum factor of safety for all species during a dry year (spring 2000), subdivided by vegetation effects

Table III. Comparison of vegetative effects on bank factor of safety (F_s) during critical conditions (bank failure) for a relatively dry year (April 2000) and wet year (February 2001)

	Gamma grass		Riparian trees		Black willow		Sweetgum		River birch		Sycamore		Switch grass	
Year	2000	2001	2000	2001	2000	2001	2000	2001	2000	2001	2000	2001	2000	2001
Bare soil F_s	0·98	0·72	0·98	0·72	0·98	0·72	0·98	0·72	0·98	0·72	0·98	0·72	0·98	0·72
Soil moisture effect	−0·10	−0·11	0·70	0·21	0·70†	0·21†	0·70†	0·21†	0·70†	0·21†	0·70†	0·21†	−0·10‡	−0·11‡
c_r effect	0·34	0·35	0·38*	0·38*	0·14	0·14	0·23	0·23	0·41	0·50	0·40	0·41	1·02	1·02
Surcharge effect	0·00	0·00	−0·07	−0·05	−0·03	−0·02	−0·06	−0·03	−0·08	−0·05	−0·07	−0·04	0·00	0·00
Net F_s	1·22	0·96	1·99	1·26	1·79	1·05	1·85	1·13	2·01	1·38	2·01	1·30	1·90	1·63

* Based on average root reinforcement values for sweetgum, river birch and sycamore.
† Based on matric suction recorded under riparian trees.
‡ Based on matric suction recorded under gamma grass.

data from one species to another limits the findings somewhat, it enables a first assessment to be made of the relative effects of each vegetation type on bank stability.

The results (Figure 8) show significant differences in F_s for the different tree species. River birch and sycamore had the greatest benefit, with an increase in F_s due to root reinforcement of 42 per cent and 41 per cent respectively. Surcharge reduced F_s by 8 per cent and 7 per cent respectively, leaving a net value of 2·01 for both species when the 71 per cent increase due to enhanced matric suction was added (105 per cent increase in F_s). Black willow and sweetgum caused much smaller increases in F_s due to root reinforcement, at 14 per cent and 23 per cent respectively. The reductions in F_s due to surcharge were 3 per cent and 6 per cent respectively, leaving net values of 1·79 for black willow (83 per cent increase), and 1·85 (89 per cent increase) for sweetgum once hydrologic effects were added. Switch grass had the greatest root reinforcement effect of any species tested, with an increase in F_s of 104 per cent. Offset by the decrease of 10 per cent due to soil moisture increases this left a net F_s of 1·9 (94 per cent increase) compared to 1·22 (24 per cent increase) for gamma grass.

Though these results are interesting, they represent vegetation effects during an unusually dry period: April 2000 followed the driest antecedent six-month period on record (18 years) at the Goodwin Creek watershed (37 per cent of mean six-month rainfall). Spring 2001 was much wetter (124 per cent of mean six-month rainfall, the fourth wettest period on record), presenting an opportunity to test the hydrologic effects of vegetation in less favourable circumstances. Figure 9 shows the vegetation cover broken down into separate effects during the February 2001 bank failure episode. Mechanical effects have been incorporated using the same values as before, with the new tensiometer values used to calculate F_s. The most striking feature is the reduction in overall stability due to wetter ground conditions and reduced hydrologic benefits in the tree species, and increased detrimental hydrologic effects in the grasses. In the case of gamma grass the net effect of vegetation was insufficient to bring net factor of safety above one, a finding validated by bank failures in the grass plot during this period. For the mixed tree cover the overall factor of safety was reduced by 37 per cent, with the hydrologic benefit reduced from 71 per cent to 29 per cent. The increase in F_s due to root reinforcement was 53 per cent, while surcharge again reduced F_s by 7 per cent. For grasses, root reinforcement increased F_s by 49 per cent and hydrologic effects reduced F_s by 15 per cent (net 33 per cent

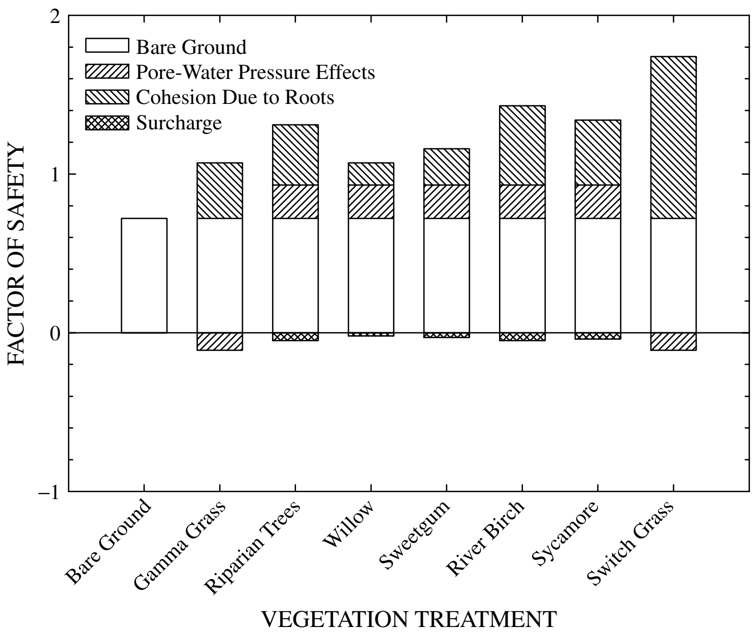

Figure 9. Minimum factor of safety for all species during a wet year (spring 2001), subdivided by vegetation effects

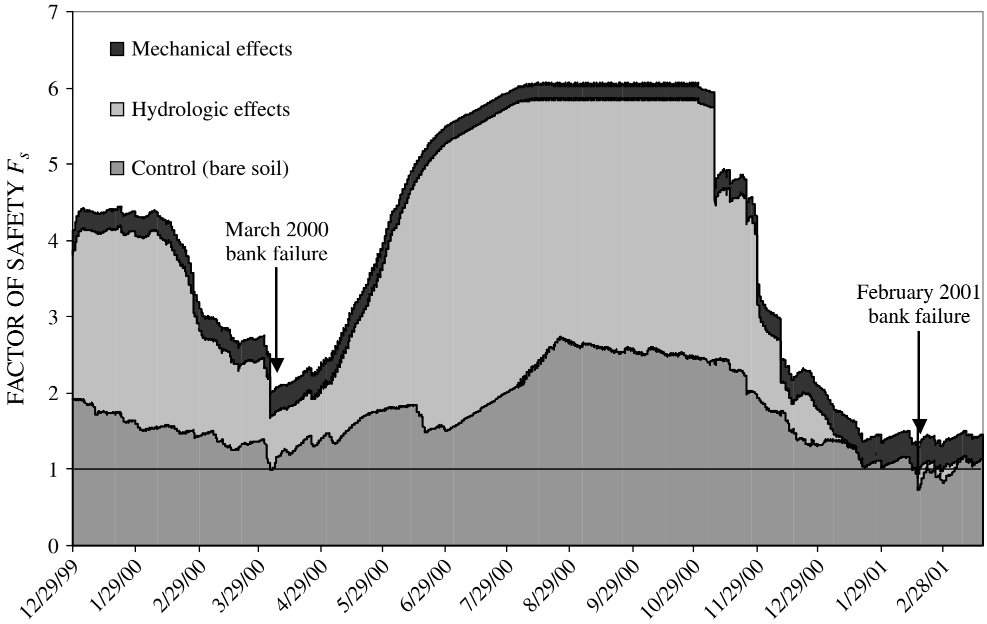

Figure 10. Factor of safety for the mixed tree cover and bare plot (December 1999–March 2001), subdivided by vegetation effects

increase in F_s). Whereas in April 2000 the hydrologic effects contributed 35 per cent of the overall F_s of the streambank and root reinforcement contributed 19 per cent, in February 2001 the pattern was effectively reversed, with hydrologic effects contributing 16 per cent to F_s and root reinforcement 30 per cent. With mechanical effects becoming more important than hydrologic effects, grasses were favoured over most tree species, with switch grass the most effective cover.

This analysis overlooks a potentially more interesting situation which occurred both before and after the period of minimum bank stability in 2001. Analysis of the tensiometer values and factor of safety during this time reveals that there were periods when the hydrologic conditions under the mixed tree plot were more *adverse* (higher positive pore-water pressures and lower matric suctions) than under the bare plot (Figure 10). During the period of greatest adverse conditions, hydrologic effects reduced the factor of safety of the mixed tree plot by 11 per cent. Although in this instance this did not coincide with periods of bank failure, it confirms that vegetation can have detrimental hydrologic effects on bank stability, when increased infiltration capacity is able to overcome the soil moisture deficit built up over the antecedent period.

DISCUSSION AND CONCLUSIONS

Vegetation increases soil strength due to the tensile strength and spatial density of its roots. This research shows great variability in both properties between different species, with the resulting increase in soil cohesion due to roots ranging from 2 to 18 kPa (averaged over the upper 1 m of soil). Of the four tree species assessed, river birch and sycamore have the strongest root networks (8 and 7 kPa respectively averaged over 1 m of soil depth) with sweetgum and black willow the weakest (4 and 2 kPa respectively). The relatively poor root reinforcing properties of black willow compared to other woody species are an interesting finding given its popularity in river restoration schemes, though to some extent this finding may be exaggerated by the slightly younger average age of our willow specimens (five years compared to seven years for sycamore and river birch). On the other hand the weakness of sweetgum is more striking, as the average age of these specimens was 10 years. Contrary to popular belief most of the reinforcement comes from a relatively small number of large roots, rather than abundant small roots. Switch grass had the strongest root network of any species tested (18 kPa), while gamma grass (6 kPa) was comparable with river birch and sycamore. The grasses gained their strength from a relatively high root area ratio, rather than stronger roots. For all species most of the increase in strength is concentrated in the upper 50 cm of soil, with little below this. At the time of minimum bank stability in April 2000, cohesion due to roots increased bank factor of safety by an average of 39 per cent for woody species, with 70 per cent for grasses. Surcharge was found not to have a very significant effect on F_s. On average it diminished F_s by 7 per cent for the tree species.

Riparian vegetation is generally considered as a mechanical aid to bank stabilization, with the hydrologic effects viewed as negligible (Coppin and Richards, 1990). A key finding of this research is that the hydrologic effects are as important as the mechanical effects, and can be either beneficial or detrimental, depending on antecedent rainfall. For the conditions investigated in April 2000, hydrologic effects (enhanced matric suction) increased F_s by 71 per cent for mixed trees. By comparison grasses produced a detrimental hydrologic effect due to increased infiltration rate and delivery of water to depth during rainfall events, and F_s was reduced by 10 per cent. The hydrologic effects were almost entirely subsurface processes: canopy interception was negligible (3 per cent of rainfall), largely due to the timing (winter/early spring when the deciduous trees were dormant) and high intensity of most rainfall. By contrast, during the wetter second period of bank instability (February 2001) the hydrologic effects of the trees increased stability by only 29 per cent, compared to 53 per cent from root reinforcement. On the gamma grass plot hydrologic effects reduced F_s by 15 per cent during this period, contributing to bank failure. Had the antecedent rainfall been slightly higher, or the timing of individual rainfall events been slightly different the hydrologic effects of the mixed tree cover could also have been detrimental. A question raised by the work is whether the detrimental hydrologic processes, combined with surcharge, can ever outweigh the beneficial effects of root reinforcement and antecedent moisture reduction. Our findings suggest that this is possible though likely to be a rare occurrence; at the time that hydrologic effects were reducing F_s on the tree plot by 11 per cent, net mechanical effects (root reinforcement minus surcharge) were increasing it by 25 per cent.

The results suggest that much more consideration needs to be given to the hydrologic role of riparian vegetation in influencing bank stability, particularly where vegetation is modified during land use change or as part of a river restoration or management scheme. Riparian zone managers seeking to use vegetation to increase streambank stability need to select species as much for their hydrologic properties as for their mechanical attributes. It is arguable that tree species should be selected for attributes such as winter/spring canopy cover and transpiration rates, overall transpiration volumes and rooting depth, as well as for mechanical factors such as root strength and root area ratio. This suggests that coniferous species may have an important role to play in bank stabilization. The research also demonstrates the potential for selected clump grasses to be used as effectively as trees to increase stability through root reinforcement. The greatest benefits will almost certainly result from mixed stands of riparian woody and grass species. This potentially would also offer the greatest benefits for riparian habitat.

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